Multi-objectives Optimization of Volumetric Shrinkage and Warpage for Disposable Mouth Mirrors Using Taguchi Method, ANOVA and Grey Relational Analysis (GRA)

J. B. Saedon, M. Z. Azlan, M. S. Adenan, and M. Azuddin

Abstract Volumetric shrinkage and warpage are the most two common defects in plastic injection moulding process that affects the overall quality characteristics of the plastics part. The use of the Taguchi optimization technique to assess and minimized volumetric shrinkage and warpage concerns that impact processing parameters during the production of disposable mouth mirrors made of Polypropylene (PP) plastic is described in this article. The process parameters that have been selected includes melting temperature, flow rate, cooling time and mold temperature during the injection moulding process simulation based on three levels and four factors in L_9 orthogonal array. The Taguchi Method was used to further analyze the simulated responses, followed by Grey Relational Analysis (GRA). The signal-to-noise (S/N) ratio graphs are examined to determine the influence of process parameters. Furthered, the Analysis of Variance (ANOVA) has been used to verify the accuracy of the optimization findings. Finally, an optimal combination of operating parameters has been proposed: melting temperature at 180 °C, flow rate at 243.6 cm^3/s, cooling time at 12 s and mold temperature at 30 °C was suggest for best optimum combination.

Keywords Parameter optimization · Taguchi method · ANOVA · Grey relational analysis (GRA) · Disposable mouth mirrors

1 Introduction

Plastic injection moulding is another key procedure for high quality goods, and it is divided into three stages: filling, packing, and cooling (together with additional

J. B. Saedon (✉) · M. Z. Azlan · M. S. Adenan
School of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
e-mail: jurisaedon41@uitm.edu.my

M. Azuddin
Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia

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mechanical actions such as mould opening, component ejection, mould closure, and molten material into the injection unit) [1]. Plastic injection moulding has several advantages as well, such as short cycle time, high quality component surfaces, excellent mechanical characteristics, low cost, and light weight. Therefore, it is becoming increasingly important in today's plastic injection industries [2]. However, like with any manufacturing process, defects might develop in the parts, causing them to be rejected during the quality control process. Weld lines, shrinkage, sink mark, and part deformation (warpage) are all regarded undesirable defects in conventional injection. Defects in goods can arise at any stage of the process. Today, several industry professionals and researchers have attempted to reduce these flaws by optimizing any of the process's features such as controlling parameter, modifying mold or material selection [3]. To manage these defects, it is important to understand the impact on injection parameters on the quality of the plastic part [1].

There are numerous existing parameter optimization techniques that are already in use. Taguchi method is one of the most well-known approaches between researchers. The Taguchi techniques were developed by Taguchi and Konishi [2]. The Taguchi technique is a comprehensive quality strategy that uses an orthogonal array to run a small number of trials and incorporates resilience into a process at the design stage [4]. Taguchi is a technique that uses a series of tests to predict the significant and insignificant factors, as well as the optimal level of the design variables. Taguchi is divided into three stages: system design, parameter design, and tolerance design. The goal of system design is to develop parts using scientific and engineering information [4].

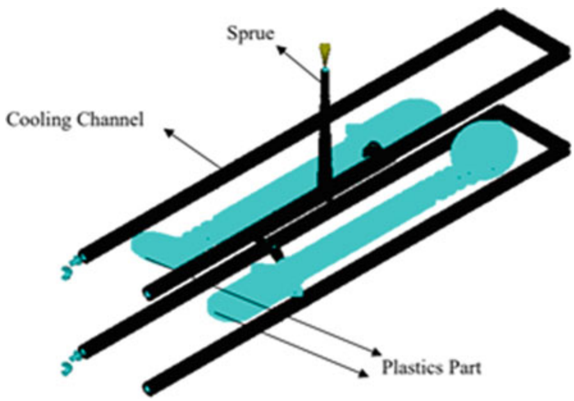
According to current study, multi-objective optimization of process parameters has emerged as new trend in the injection moulding process [5]. Many academics have focused their energy and resources to optimizing process parameters. Researchers frequently depend on their experience and a trial-and-error technique to determine the best process parameter settings for the plastics part based on plastic injection moulding process by utilizing the Taguchi approach [6]. Li et al. [5] studies the multi-objective optimization of the fiber reinforced composite using Taguchi, RSM and NSGA-II. Sreedhan et al. [7] integrated the Taguchi, ANOVA and Grey Relational Analysis (GRA) method to identify the effect of molding parameters on sink mark and weld line for ABS product. Kitayama et al. [8] examine the cooling performance, short cycle time and warpage reduction using conformal cooling channel and the multi-objective optimization using ANOVA and neural network. Oliaei et al. [9] investigates the influences of five significant process parameters in minimizing the warpage and shrinkage on polylactic acid (PLA) of biodegradable plastic spoon part. The study coupled the Taguchi approach with ANOVA and ANN by collecting the data from computer aided engineering (CAE) software tools Autodesk Moldflow™ Plastics. From the previous research, it can be concluded that parameter optimization and finite element analysis software works well in minimizing the product defects for plastic injection moulding process. In addition, the Design of Experiment (DOE) can also aid in determining the responses of change in factor values. This method works very well for injection molding product and process design in terms of selecting the optimal combination of levels of the elements that impact the process, and quality of the product.

This article addresses the use of computer aided engineering (CAE) technology for the injection moulding of a disposable mouth mirror made of Polypropylene (PP) utilizing the Moldflow Plastic Insight Package. Design of experiment (DOE)—L9 Orthogonal array was utilized to plan outline of the simulation. Four controlling parameters were chosen: melting temperature, flow rate, cooling time and mold temperature which each of the parameters having three levels. The Taguchi Method was used to further analyze the simulated responses, followed by Grey Relational Analysis (GRA). The signal-to-noise (S/N) ratio graphs are examined to determine the influence of process parameters. Furthered, the Analysis of Variance (ANOVA) has been used to verify the accuracy of the optimization findings using Minitab 19 software.

2 Experimental and Test Details

This study's aims to discover the optimum operating parameter that impacts the disposable mouth mirror on the plastic injection moulding process by utilizing the combined Taguchi technique, ANOVA and Grey Relational Analysis. Disposable mouth mirror is an essential dental tool that must be used by all dental practitioners for a variety of reasons, including allowing indirect vision of the inspected area of any part of the oral cavity, reflecting the light onto desired surfaces where direct light does not reach, retracting the lips, cheek and tongue and viewing tartar problems behind the last tooth [10]. In this study, a multi-cavities of disposable mouth mirror have been developed by using Moldflow™ Plastics Insight (MPI) software packages. Figure 1 display disposable mouth mirror settings together with feeding system. This chosen component weights 8 g, has a mirror diameter of 24 mm, a length of 160 mm, a density of 1.004 kg/m^3 and a volume of 5.03×10^{-6} m^3. This part has a 45° angle

Fig. 1 Disposable mouth mirror model analysis



between the shank and the working area (mirror), it was developed with a 40 mm long gripping area on a handle and a 7 mm thick handle with overall length of the part 160 mm. The 3D part of disposable mouth mirror undergoes the meshing process Moldflow™ Plastics Insight (MPI). This section has a 3D mesh of 127,286 triangle elements, 63,671 nodes, and 50 sprue, runner, and gate elements. The sprue diameter is 3 mm with a length of 60 mm, and the runners have a diameter of 3 mm. Based on the simulation, this part total volume including sprue, runner and gate are 11.95 cm^3. Meanwhile, total volume for two parts (multi-cavity) of disposable mouth mirror is 10.0233 cm^3.

2.1 Parameter Optimization Method

To identify the optimal operating parameter, designs of experiment (DOE) rely mostly on one of the Taguchi techniques. This method was utilized to enhance the designs of disposable mouth mirror. A set of orthogonal arrays then was integrated into the Moldflow™ packages on the disposable mouth mirror. Then, data generated from the simulation results has been analyzed in signal to noise ratio to determine the best operating parameter for the selected output. ANOVA was used to identify the most significant effect affects the products defect i.e., volumetric shrinkage and warpage. Grey relational analysis was integrated to identify the multi-objective optimization of volumetric shrinkage and warpage on the disposable mouth mirror. To validate the findings obtained from the optimization technique, a confirmation test was performed. If there is no improvement in the proportion of defects on the product, the procedure will be repeated to discover the best operating parameter. Parameter optimization process has been done using Minitab 19 software.

In this study, four injection moulding parameters will be investigated: melting temperature, flow rate, cooling time, and mold temperature, along with three levels, to decrease part shrinkage and warpage. Based on literature and the current best practice, the range of the selected parameter has been specified as in Table 1. The parameters used were determined using a simulated analysis procedure utilizing results generated by Autodesk Moldflow™ Plastics Insight.

Table 1 Controlling Parameters and Their Levels

Symbol	Parameters	Unit	Level 1	Level 2	Level 3
A	Melting temperature	°C	180	200	220
B	Flow rate	cm^3/s	162.4	203	243.6
C	Cooling time	s	8	10	12
D	Mold temperature	°C	30	50	70

Table 2 Mechanical properties of polypropylene

Parameter	Value
Melt temperature (°C)	191–263
Injection mould temp. (°C)	27–66
Tensile strength (MPa)	55.2
Shrink rate (%)	0.1–0.3
Density (kg/m^3)	728.28
Melt flow index (g/min)	0.2

2.2 Material Selection

The material selection and characteristics are specified by computing polypropylene with 20% glass fiber filler by weight into the software material selection data. This material settings on the Moldflow™ software is based on manufacturer Avient with serial number Trilliant™ HC HC5210-0020 RS Natural based on the manufacturer's technical data sheet. Polypropylene (PP) was selected as the molten material for disposable mouth mirrors because of the low melt viscosity, the plastics flow very smoothly, especially in small spaces like the grip region on the handle. The shrinkage rate of polypropylene is around 0.1–0.3%, although the numbers vary depending on the number of variables and the governing factors. Table 2 illustrates the mechanical characteristics of the polypropylene utilized in this investigation based on the scientific data sheet.

3 Results and Discussion

3.1 Signal to Noise (S/N) Ratio

The Taguchi approach suggests a signal to noise (S/N) ratio to identify the quality characteristics to be considered for any engineering design challenge. The S/N ratio has three phases: the smaller the better, nominal is the best and the bigger the better [4]. In this study, the smaller the better-quality characteristics is chosen to minimize volumetric shrinkage and warpage by controlling each process parameter to the optimal level. The S/N ratios for the nine trials were computed and results are shown in Table 3. The computed results of S/N ratio for both volumetric shrinkage and warpage were ranges between 9.923 and 11.57% for volumetric shrinkage and 3.09–3.414 mm for warpage, respectively. It can be concluded that experiment number 8 yields the highest value of volumetric shrinkage, meanwhile experiment number 4 gave a highest value for warpage.

Table 4 shows, the S/N ratio response table for volumetric shrinkage and warpage. The results show that the following are the best process parameter combinations for

Table 3 S/N ratio for volumetric shrinkage and warpage as response parameter

Orthogonal array					Output			
Run No.	A	B	C	D	Volumetric shrinkage (%)	Volumetric Shrinkage, S/N ratio	Warpage (mm)	Warpage, S/N ratio
1	180	162.4	8	30	9.923	−19.932	3.188	−10.070
2	180	203	10	50	10.36	−20.307	3.173	−10.029
3	180	243.6	12	70	10.45	−20.382	3.090	−9.7991
4	200	162.4	10	70	10.73	−20.611	3.414	−10.665
5	200	203	12	30	10.77	−20.644	3.180	−10.048
6	200	243.6	8	50	11.15	−20.945	3.175	−10.034
7	220	162.4	12	50	11.48	−21.198	3.374	−10.562
8	220	203	8	70	11.57	−21.266	3.369	−10.550
9	220	243.6	10	30	11.56	−21.259	3.170	−10.021

Table 4 Response table of S/N ratio for volumetric shrinkage and warpage

Level	Factors				Level	Factors			
	Volumetric shrinkage					Warpage			
	A	B	C	D		A	B	C	D
1	−20.21	−20.58	−20.72	−20.61	1	−9.97	−10.43	−10.22	−10.05
2	−20.73	−20.74	−20.73	−20.82	2	−10.25	−10.21	−10.24	−10.21
3	−21.24	−20.86	−20.74	−20.75	3	−10.38	−9.95	−10.14	−10.34
Delta	1.03	0.28	0.03	0.21	Delta	0.412	0.481	0.102	0.291
Rank	1	2	4	3	Rank	2	1	4	3

volumetric shrinkage: $A_1 B_1 C_1 D_1$ these variations correspond to a melting temperature of 180 °C, a flow rate of 162.4 cm^3/s, a cooling time of 8 s, and a mold temperature of 30 °C. Indicating the response value for volumetric shrinkage of disposable mouth mirror on multiple cavities at A_1 (−20.21), B_3 (−20.58), C_3 (−20.72), D_1 (−20.61). Based on the table, the rank indicating the most influential parameters to the shrinkage contribution. It revealed that the order of significance of each parameter on volumetric shrinkage is A > B > D > C. Figure 2 shows, the main effects plot for volumetric shrinkage, it is clearly showing that melting temperature parameter gives the most influential parameter to the occurrence of volumetric shrinkage follows by flow rate, mold temperature and cooling time. Meanwhile Fig. 3 shows, the main effects plot for warpage.

Meanwhile, the most optimal parameter combination for warpage is $A_1 B_3 C_3 D_1$. These variations correspond to a melting temperature of 180 °C, a flow rate of 243.6 cm^3/s, a cooling time of 12 s, and a mould temperature of 30 °C, indicating the response value for warpage for disposable mouth mirror on multiple cavities at A1 (−9.966), B3 (−9.952), C3 (−10.137), and D1 (−10.047). The importance of each

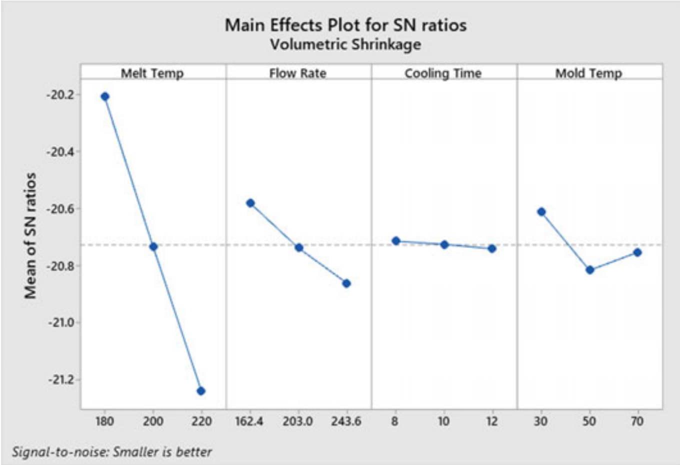


Fig. 2 Main effects plot for S/N ratios of volumetric shrinkage

design parameter for warpage is evaluated and found to be B > A > D > C. According to results, flow rate is the most significant element in reducing warpage. This might be because the flow rate of the disposable mouth mirror changes constantly throughout the filling stage.

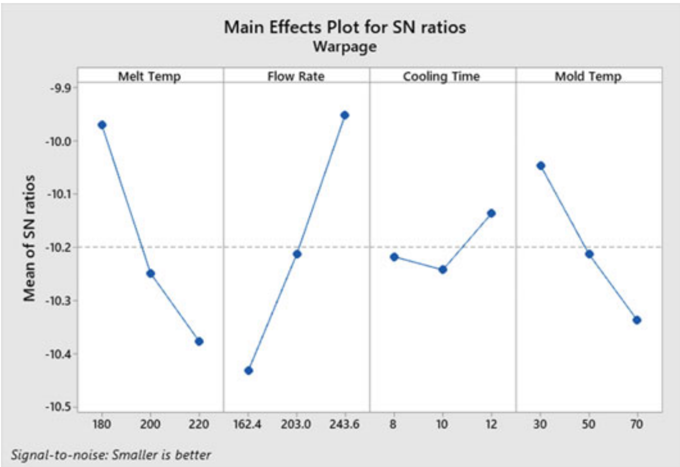


Fig. 3 Main effects plot for S/N ratios of warpage

3.2 Analysis of Variance (ANOVA)

The goal of ANOVA is to identify the statistically significant parameters impacting quality characteristics in a specific experimental study [5]. Table 5 shows, the ANOVA table for volumetric shrinkage defect. It shows melting temperature parameter gave the highest percentage contribution of (90.26%), furthermore, the F value for melting temperature recorded is 10.3517 proved that this parameter gave the most significant im- pact on the part. Meanwhile, flow rate (6.44%), cooling time (0.02%) and mold temperature (3.28%). From the table, it shows that the most influence parameter meets the results from S/N response table. This results match those observed in earlier studies that found that melting temperature gave the highest contribution to volumetric shrinkage as found in [11].

Table 6 shows, the ANOVA statistical results for warpage. It is apparent from this table that each parameter gave a significant value of contribution for warpage on disposable mouth mirror. The most significant parameter is flow rate with 45.56% and F value of 135.97613. Follows with melting temperature (34.75%), mold temperature (17.50%) and lastly cooling time (2.19%). However, the F value for each parameter results in higher than F > 4, meaning that all controlling parameters gave an impact on the occurrence of warpage. From this observation, it clearly shows, cooling time resulted in the lowest value of contribution for both volumetric shrinkage and warpage. The present findings seem to be consistent with other research which found

Table 5 ANOVA table for volumetric shrinkage

Symbol	Parameters/factors	DOF	SS_T	SS_m	F	ρ (%)
A	Melting temp	2	2.51829	1.25914	10.3517	90.26
B	Flow rate	2	0.17975	0.08987	0.73890	6.44
C	Cooling time	2	0.00057	0.00028	0.00234	0.02
D	Mold temp	2	0.09148	0.04574	0.37605	3.28
	All other/error	0		0.12163		
	Total	8	2.79010	0.34876		100.00

Table 6 ANOVA table for warpage

Symbol	Parameters/factors	DOF	SS_T	SS_m	F	ρ (%)
A	Melting temp	2	0.0372	0.01862	103.72390	34.75
B	Flow rate	2	0.0488	0.02442	135.97613	45.56
C	Cooling time	2	0.0023	0.00117	6.53791	2.19
D	Mold temp	2	0.0187	0.00938	52.24278	17.50
	All other/error	0		0.00017		
	Total	8	0.1072	0.01340		

that melt and mold temperatures, packing pressure, and cooling time are all proved to be significant factors in presence of warpage for injection-molded part.

3.3 Grey Relational Analysis (GRA)

The grey relation analysis is primarily a quantitative investigation of the hierarchical operation. It calculates the degree of vicinity based on similarities or differences between variables after normalized. The optimum set of values for the parameters will be determined in GRA analysis.

Table 7 shows, the grey relation coefficient and grey relational grade for all 9 experiments after normalization has been calculated for all experiments. The values of grey relational grade, which is the weighted sum of the grey relational coefficient, were rated for the whole run, from higher to lower values. The greater the value of grey relation- ship grade, the better the various performance characteristics. As a result, the multi- objective optimization issue has been reduced to a single-objective optimization problem. In Table 7 shows the greatest relationship grade values of 0.85 in experiment number 1. It can thus be inferred from all nine trials that experiment number 1 offers the finest multi-response characteristics.

Grey relational influence parameters were highlighted by bold type where the higher values were given for all three levels, as the most affected parameters as in Table 8. From the table, the results shows that the best combination is $A_1B_3C_3D_1$ indicating melting temperature—180 °C, flow rate—243.6 cm^3/s, cooling time—12 s and mold temperature—30 °C.

The analysis of the variance (ANOVA) is used for the overall mean of the Gray Relational Grade to get the most significant process parameters. The ANOVA performance criterion results with computed F value of each component are shown in Table 9. From the results, melting temperature shows the greatest contribution to the

Table 7 Grey relation coefficient and grey relational grade values

Orthogonal array					GRC		GRG	Order
Run No.	A	B	C	D	Shrinkage	Warpage		
1	1	1	1	1	1	0.6975	0.85	1
2	1	2	2	2	0.7347	0.7438	0.74	3
3	1	3	3	3	0.6800	1	0.84	2
4	2	1	2	3	0.5100	0	0.25	7
5	2	2	3	1	0.4857	0.7222	0.60	4
6	2	3	1	2	0.2550	0.7377	0.50	5
7	3	1	3	2	0.0546	0.1234	0.09	8
8	3	2	1	3	0	0.1389	0.07	9
9	3	3	2	1	0.0060	0.7531	0.38	6

Table 8 Influence parameters on grey relational grade

Symbol	Parameters/Factors	Unit	Level 1	Level 2	Level 3
A	Melting temperature	°C	**0.81**	0.45	0.18
B	Flow rate	cm^3/s	0.39	0.47	**0.57**
C	Cooling time	sec	0.47	0.45	**0.51**
D	Mold temperature	°C	**0.61**	0.44	0.38

Table 9 ANOVA table on volumetric shrinkage and warpage

Symbol	Parameter/factors	DOF	SS_T	SS_m	F	ρ (%)
A	Melting temp	2	0.5994	0.2997	35.10288	81.09
B	Flow rate	2	0.0488	0.0244	2.857892	6.60
C	Cooling time	2	0.0056	0.0028	0.327955	0.76
D	Mold temp	2	0.0854	0.0427	5.001312	11.55
	All other /Error	0		0.0085		
	Total	8	0.7392	0.0924		100.00

process control with 81.09% contribution in the existence of volumetric shrinkage and warpage on the disposable mouth mirror. Followed by mold temperature with 11.55% and flow rate 6.60%. In contrast to earlier findings, however, no evidence of cooling time gave a significant impact on the product defects. This may be due to the parameters controlled on the simulation software does not meet the actual phenomenon of the cooling time. Meanwhile the F value for melting temperature recorded the higher value with 35.1028 and higher than $F > 4$ and follows with mold temperature which is 5.0013. This prove that melt temperature and mold temperature are two most significant parameter in product defects performance. This finding supports previous research into the correlation of product defect between melt and mold temperature.

3.4 Validation and Confirmation Test

In this section, a validation and confirmation test has been run in the Moldflow simulation software package based on the best combination of parameters that has been discovered in Grey relational analysis. Table 10 shows, the confirmation test using the optimal simulated parameters. The optimum process parameters combination for achieving minimum volumetric shrinkage and warpage are; melt temperature 180 °C, flow rate 243.6 cm^3/s, cooling time 12 s, and mold temperature 30 °C. As presents in Table 10, the volumetric shrinkage has been minimized from 11.57% to 9.928% which showing 14.19% improvement, while warpage also shows an improvement

Table 10 Confirmation test for volumetric shrinkage and warpage

	Initial simulation parameter	Optimal parameter		% Improvement
	Orthogonal Array	Prediction by GRA	Confirmation Experiment	
Setting level	$A_3B_2C_1D_3$	$A_1B_3C_3D_1$	$A_1B_3C_3D_1$	
Shrinkage	11.57		9.928	14.19
Warpage	3.369		1.265	62.45
Grey relational grade	0.07		0.99	
Improvement of the Grey Relational Grade = 0.92				

at 62.45% which the value has been decrease from 3.369 to 1.265 mm. This validates the efficiency of Taguchi DOE and Grey relational analysis in identifying the multi-objective optimization to find the best combination of parameter.

4 Conclusion

The CAD/CAE/DOE has been presented, to optimize parameters of the injection molding process with the multiple performance characteristics. Using Taguchi experimental design, the volumetric shrinkage and warpage of an injection molding process have been independently optimized by four control variables particularly melting temperature, flow rate, cooling time and mold temperature for the purposes of a disposable mouth mirror analysis. The application of gray relational analyzes the volumetric shrinkage and warpage can turn multi-performance optimization into the optimization of one performance feature known as the gray relational grade. This technique can therefore considerably simplify the optimization of the complex multiple performance criteria. For this investigation, the best injection-molding process parameter; melting temperature, level 1: 180 °C, flow rate, level 3: 243.6 cm^3/s, cooling time, level 1: 12 s and mold temperature, level 1: 30 °C.

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References

1. López A, Aisa J, Martinez A, Mercado D (2016) Injection moulding parameters influence on weight quality of complex parts by means of DOE application: case study. Meas J Int Meas Confed 90:349–356
2. Oktem H, Erzurumlu T, Uzman I (2007) Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. Mater Des 28(4):1271–1278
3. Khan RM, Acharya G (2016) Plastic injection molding process and its aspects for quality: a review. Eur J Adv Eng Technol 3(4):66–70
4. Moayyedian M, Abhary K, Marian R (2016) Gate design and filling process analysis of the cavity in injection molding process. Adv Manuf 4(2):123–133
5. Li K, Yan S, Zhong Y, Pan W, Zhao G (2018) Multi-objective optimization of the fiber-reinforced composite injection molding process using Taguchi method, RSM, and NSGA-II. Simul Model Pract Theory 91:69–82
6. Kuram E, Tasci E, Altan AI, Medar MM, Yilmaz F, Ozcelik B (2013) Investigating the effects of recycling number and injection parameters on the mechanical properties of glass-fibre reinforced nylon 6 using Taguchi method. Mater Des 49:139–150
7. Sreedharan J, Jeevanantham AK (2018) Optimization of injection molding process to minimize weld-line and sink-mark defects using Taguchi based grey relational analysis. Mater. Today Proc. 5(5):12615–12622
8. Kitayama S, Miyakawa H, Takano M, Aiba S (2017) Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel, pp 1735–1736
9. Oliaei E et al (2016) Warpage and shrinkage optimization of injection-molded plastic spoon parts for biodegradable polymers using Taguchi, ANOVA and artificial neural network methods. J Mater Sci Technol 32(8)
10. Chetan D (2011) Mouth mirror (dental mirror)—parts, types and functions. [Online]. Available: https://www.drchetan.com/mouth-mirror.html
11. Ramakrishnan R, Mao K (2017) Minimization of shrinkage in injection molding process of acetal polymer gear using Taguchi DOE optimization and ANOVA method. Int J Mech Ind Technol 4(2):72–79